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Current Directions in the Vulnerability/Lethality Process Structure

James N. Walbert
Lisa K. Roach
Mark D. Burdeshaw

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James N. Walbert, Lisa K. Roach, Mark D. Burdeshaw

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An important aspect of the formulation of any scientific process is the definition of the mathematical framework within which that process is considered. This mathematical basis defines the limitations of the process, provides the means for conducting analyses, and helps ensure uniformity and consistency of results. It is quite common for analytical processes to evolve over a long period of time before the underlying mathematics is fully understood and illuminated. This is the case with Vulnerability/Lethality (V/L) analysis, long considered more an art than a science. In recent years, advances have been made in the rigorous mathematical treatment of certain areas of V/L analysis. In this report, the unifying mathematical framework for all V/L analysis is defined, demonstrating how each part of a well-known process fits into this framework, and illustrating the framework's growth potential. The Degraded States Vulnerability Methodology (DSVM) will be shown to provide an important example of the rigor with which one part of a vulnerability analysis may be conducted, specifically, the formulation of target capability measures from the damaged state.

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I. Introduction

An important aspect of the formulation of any scientific process is the definition of the mathematical framework within which that process is considered. This mathematical basis defines the limitations of the process, provides the means for conducting analyses, and helps ensure uniformity and consistency of results. It is quite common for analytical processes to evolve over a long period of time before the underlying mathematics is fully understood and illuminated. This is the case with Vulnerability/Lethality (V/L) analysis, long considered more an art than a science. In recent years, advances have been made in the rigorous mathematical treatment of certain areas of V/L analysis.[1] In this report, the unifying mathematical framework for all V/L analysis is defined, demonstrating how each part of a well-known process fits into this framework, and illustrating the framework's growth potential. The Degraded States Vulnerability Methodology (DSVM) will be shown to provide an important example of the rigor with which one part of a vulnerability analysis may be conducted, specifically, the formulation of target capability measures from the damaged state.

II. Background

Traditionally, the V/L analysis process has been that of inferring some loss of effectiveness, or combat utility, from damage inflicted by a munition on a combat system. The association of remaining utility with damage has been accomplished by a wide variety of means, from intuitive inference to empirical correlations to Monte Carlo simulations on computers. Among the numerous difficulties with this process is defining "effectiveness" or "utility," since these terms tend to be related to particular mission or combat scenarios. Conclaves of experts in military science have been convened for the purpose of providing estimates of utility, generally expressed as a percentage, given the loss of certain combinations of components or subsystems on a particular vehicle.[2] Such estimates, or Damage Assessment Lists (DALs), use intuitive inference to link component damage to loss of combat utility. These estimates represent a kind of average over all possible missions for the vehicle, and are therefore devoid of detail about specific system capabilities. The most common interpretation of these estimates (an incorrect one, as emphasized by Starks[3]) is as a probability of complete "kill," in either mobility or firepower or both.

The Ballistic Vulnerability/Lethality Division (BVLD), Survivability/Lethality Analysis Directorate (SLAD), of the U.S. Army Research Laboratory (formerly the U.S. Army Ballistic Research Laboratory), has developed improved metrics for use in vulnerability assessments.[4,5] These metrics are used in the new DSVM which identifies the major functional capabilities of a combat system and a set of degraded capabilities within each of the functional categories. Killed components for a given target/warhead interaction are mapped into these degraded capabilities through fault tree analysis. This mapping permits calculation of the probabilities of the system being in one or more degraded capabilities. This methodology avoids the aforementioned oversimplification in the DAL process, and provides the foundation for more detailed analyses than were possible previously. The DSVM is described in greater detail later in this report.

In the late 1950s, a series of tests at the Canadian Armament Research and Development Establishment (CARDE) represented the first modern attempt at extensive collection of empirical data to relate damage to loss of function.[6] From these CARDE trials came a number of correlation curves relating hole sizes in armor to loss of capability. Extensions of these curves are still used today, even though in many cases the combat systems to which they are applied bear little resemblance to those tested at CARDE. The unfortunate effects of this extrapolation are pervasive, even infecting computer codes written 30 years after the tests.

In the cases of aircraft and ships, although current analytical practices are different, many of the same shortcomings apply. For aircraft, vulnerability analyses have long included performance-oriented measures of effectiveness (MOE); examples of these include "Forced Landing", "Time-dependent Crash Landings", etc. However, along with additional mission-oriented MOEs, such as "Mission Abort", aircraft V/L analyses traditionally suffer from similar logical disconnects between weapon effects and target response. In the case of ship analyses, several shortcomings apply. Therefore, although the language of this report is cast in terms of armored vehicles, the applicability of the concepts is universal.

Computer models which have evolved to assist in this analysis process are a reflection of the level of understanding the analysts have of the various physical and engineering phenomena involved. The lumped-parameter model known as the Compartment Model, for example, assumes each system consists of "black box" compartments such as ammunition, crew, and engine.[7] A perforation by a munition anywhere into one of these compartments results in a standard type of loss of function; that is, all components in the compartment are "lumped" into a single group for analysis. Another class of models, Point Burst, includes more extensive component descriptions and attempts to distinguish between different shot lines by tracing the lines through a detailed target description (see also Reference 7).

Around 1985, the task of making pre-shot predictions for the Abrams tank live-fire tests underscored the widely known fact that deterministic models fail to represent adequately the uncertainties of projectile impact attitude, armor and component fracture mechanics, spall production, fragment ricochet, and numerous other factors involved in damaging a combat system. Stochastic or Monte Carlo techniques were introduced in an attempt to provide more realistic estimates of damage to vehicles. For an historical perspective on vulnerability testing and modeling, the reader is directed to reference 8. In that paper, Deitz and Ozolins recognized the need to understand more rigorously the analytical processes and relationships by introducing the concept of spaces for V/L analysis. These spaces and the mappings between them have been used in a number of papers over the past several years. [8 9 10 11 12] Although there is no question that the notion of spaces has been heuristically useful, there have been both changes in usage and a lack of mathematical precision in the ongoing dialogue. It is thus important to make rigorous the complete taxonomy with its definitions, assumptions, and limitations. What follows is a description of the spaces and mappings, as well as a detailed discussion of the application of this taxonomy to V/L analyses.

It is anticipated that the framework presented in this report will pervade much of the future work in vulnerability and lethality, both theoretical and empirical. In fact, the terminology discussed herein has already become part of the working vocabulary in the community.

III. Vulnerability within Survivability and Lethality

In the context of this report, the term "vulnerability analysis" refers to the evaluation of the effects of a warhead on a target. This excludes consideration of such factors as acquisition, munition flight, etc. Similarly excluded are mission/scenario factors that describe the effect of the resulting damage upon combat utility. This relationship is illustrated in Figure 1.

IV. V/L Spaces and Mappings

1. V/L Levels and Spaces

The basis for the taxonomy of V/L Spaces comes from the recognition that V/L analyses pass through distinct levels of information in a precise order. These levels are:

1. Threat-Target Interaction, or Initial Configuration (including Initial Conditions),

2. Target Component Damage States,

3. Target Degraded Capability States, and

4. Target Battlefield Utility.

From the Target Degraded Capability States can be derived the various mission-oriented losses of function such as "Firepower Loss of Function (LOF)" and "Mobility LOF".

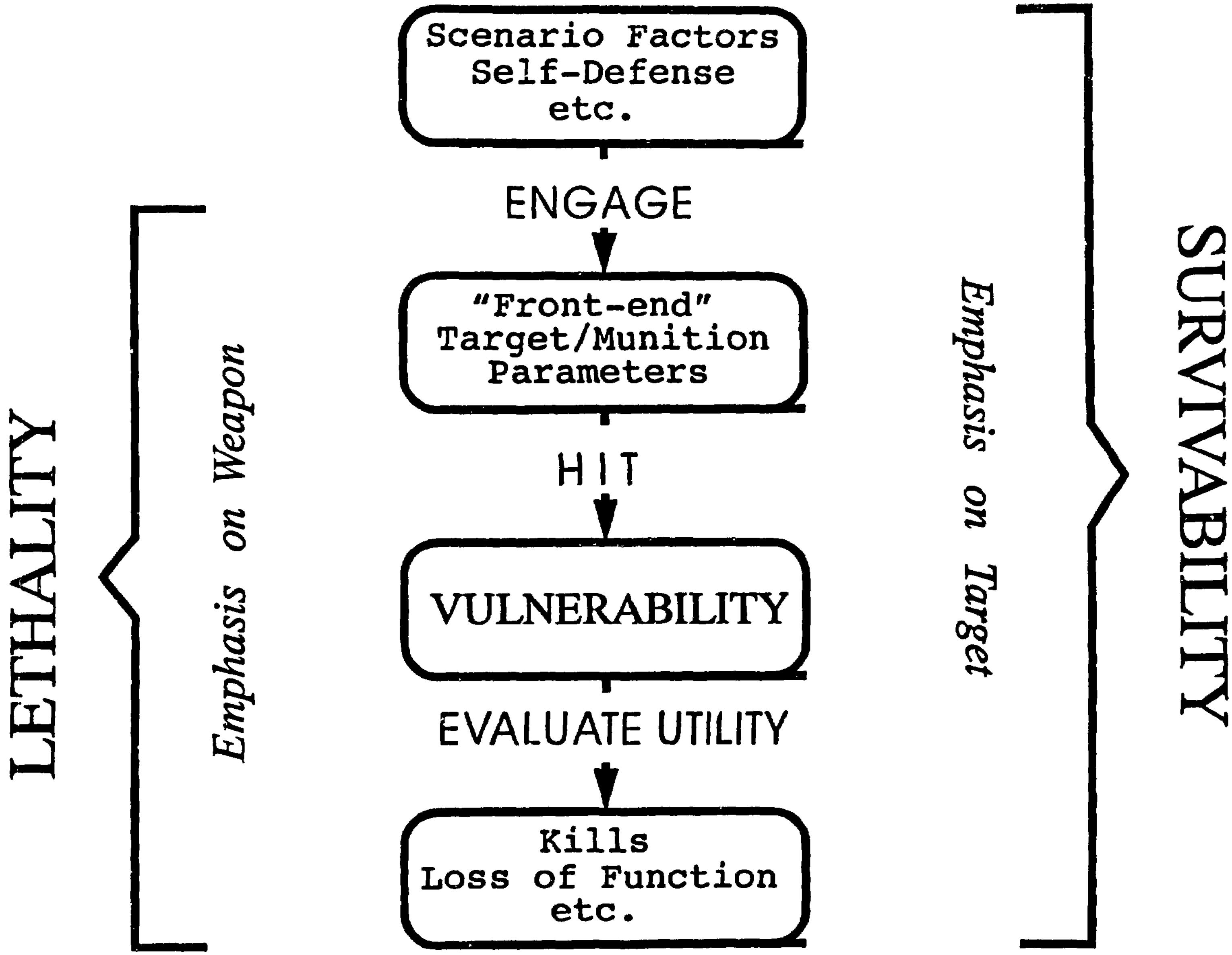

Figure 1. The Relationships Between Vulnerability, Lethality and Survivability

The mappings by which one passes from one level to the next are dependent on different kinds of information at each level. For example, going from Level 1 to Level 2 (threat-target initial configuration to target damage) essentially involves physics; going from Level 2 to Level 3 (target damage to degraded capability) requires engineering measurement. The process can be shown pictorially as in Figure 2.

It is important at the outset to differentiate between "Levels", which are composed only of states of existence, and the "mappings", operators -- with the data and algorithms to which they have access -- which relate a state at one level to a state at another.

A *Level* contains all the information required to define the state of the system at the associated stage of a V/L analysis/experiment. At each level, one can define a space of points, each point being a vector whose elements correspond to the status of a particular entity related to the target. For example, in Space 2 (Damage States), each element may refer to the status of a particular component/subsystem. The spaces thus defined are the "V/L Spaces", and represent, at each level, the state of the target system.

A *Mapping* represents all of the information (physics, engineering, etc.), known or unknown, required to associate a point in a space at one level with a point in a space at the next level. Mappings have access to information such as: fundamental data (penetration parameters [Level 1 to Level 2], leakage rates [Level 2 to Level 3], etc.); intermediate data generated by the mapping (line-of-sight thicknesses [1 to 2], temperature rise in an uncooled engine [2 to 3]); and algorithms (depth of penetration [1 to 2], fault trees [2 to 3]).

The V/L experimental and analytical processes can then be expressed as a series of mappings which relate a state vector in one space (the domain) to a resultant state vector in a next higher-level space (the range).

Note that at each transition to the next level some detail about the target system may be lost: a broken bolt in level 2 may be the cause of degraded mobility influencing mission effectiveness, but at level 3 the bolt is no longer recognized as an entity. It is now widely acknowledged that skipping over levels (such as inferring remaining combat utility directly from the size of the hole in the armor) loses so significant an amount of information that continuity and auditability are lost.

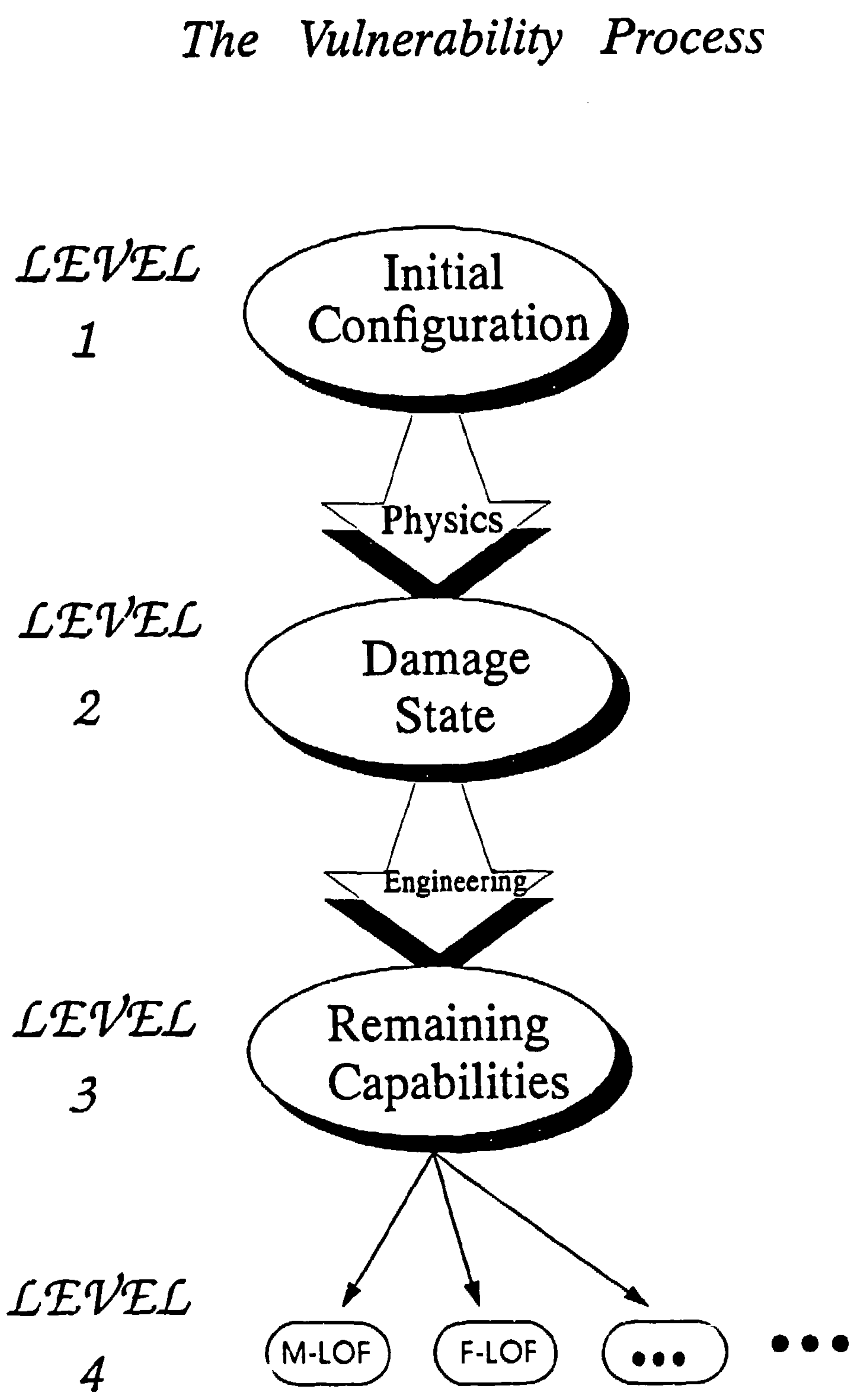

Figure 2. The Vulnerability Analysis Process

2. Axioms and Definitions

In order to provide a consistent structure to the taxonomy about to be defined, the following axioms (assumptions) are given:

1. There are three levels of information making up the vulnerability analysis universe; spaces can be defined at each of these levels.

2. The points in each of the spaces are, in principle, observable and/or measurable.

3. The points in each space are vectors, consisting of one or more elements.

4. There exist mappings from each level to the next, specifically from a point in a space at each level to a corresponding point in a space at the next level.

With these axioms in place:

Definition 1:

1. V/L Space 1, or VL1, is a set of possible initial configurations for target/munition interaction.

2. V/L Space 2, or VL2, is the set of all possible damage vectors which can result from the initial configurations contained in VL1. The elements of the vectors in VL2 indicate the status of all critical components/subsystems.

3. V/L Space 3, or VL3, is the set of all possible system capability degradation vectors resulting from the damage states in VL2. The elements of the VL3 vectors indicate degrees of capability (for movement, communication, firepower -- or, at a finer level of resolution, speed, acceleration, etc.)

Definition 2: The dimension of a space is the number of elements in a vector (point) in that space.

Definition 3: The cardinality of a space is the number of vectors (points) in that space.

Definition 4: The mapping from VL1 to VL2 is denoted by O12; similarly, the mapping from VL2 to VL3 is denoted by O23.

It is important to recognize that it is possible to construct many different spaces at any particular level. For example, note that the number of elements in a point (vector) in a space may depend upon the granularity of the target description to be used. This appears to be practically unavoidable: a human enumerates the different elements which will be evaluated in deciding what state exists after a single shot. Thus, there may be any number of spaces which could be created to describe the post-shot evaluation. Yet, they could all be "Spaces", as defined in this section. (That is, they can be closed, possess an identity element, be amenable to the defined operators, etc.)

A potentially fruitful area for future study is the relationship between different spaces at the same level that differ only in their degrees of granularity. This naturally leads to the concept of an "ultimate" space at each level. For example, consider a sequence of spaces of damage vectors (level 2), each succeeding space having more elements in its vectors. Since each element of a damage vector refers to the status of a particular part of the target, such a sequence could result from a progressively finer dissection of the target into successively smaller parts. The endpoint of this sequence is a construct whose discrete elements are replaced by continuously varying ones which detail the infinitesimal, point-by-point status of the target. Ideally, this "endpoint" will also form a space under the same definitions that are listed herein, with the necessary replacement of discrete entities with continuous ones.

The relationship between this "ultimately fine space" and a space of coarser granularity may be of more than academic interest. For example, suppose a predictive result is expressed in terms of a set of damage vectors assembled into space VL2a. An experiment is independently conducted, with results expressed in terms of the damage vectors in VL2b. Consider the task of determining how close the prediction is to the experimental result. Since the spaces are different, comparison of the damage vectors, in a mathematical sense, may be unfounded. However, if both results can be related to their associated points in VL2* (the "ultimately fine space"), a comparison between the points can be made.

3. Relationships Between Spaces at Different Levels

a. **Mappings.** Next, consider the mappings, the association of points from a space at one level with those in a space at another level. As described above, the points in the spaces are determined by system design, construction, and intended application; specifically excluded are the physical and engineering factors that relate points in one space (for example, a set of initial conditions) to points at the next level (for example, the resultant damage). Rather, such factors are incorporated in the mappings, either actually, if the mapping is accomplished by a field experiment, or algorithmically, if the mapping is accomplished by analysis or simulation. Analytical mappings are characterized by empirical or theoretical relationships such as penetration algorithms, fracture mechanics, etc., in the case of the mapping from VL1 to VL2. When going from VL2 to VL3, an analytical mapping is essentially an engineering performance model, supported by a series of fault trees which describe the logical connections between components to form subsystems. Thus, in this taxonomy, knowledge gaps are quite clearly linked to the ability to construct a mapping from one space to another.

As an example of the O23 mapping process, the DSVM maps the target damage state into its remaining capability state. For an armored fighting vehicle, the vehicle's required capabilities could be described in terms of a six-element vector (Mobility, Firepower, Acquisition, Crew, Communications, Ammunition). Conventional DS terminology refers to these elements as "capability categories"; each DS capability category is further divided into capability levels which define a particular performance degradation (i.e., reduced speed, reduced accuracy, etc.). Included within a capability category are all possible combinations of capability levels that could occur simultaneously and a "no damage" capability level. These two properties of the capability category make the capability levels within a category both mutually exclusive and exhaustive. For any set of components, one and only one capability level will be satisfied for each capability category. This combination of capability levels, one from each category, represents the degraded state of the vehicle. This methodology provides a more robust set of metrics when compared to the traditional DAL metrics which provide only a single LOF value for both mobility and firepower, as demonstrated by the example later in this report.

Mathematical fault trees are developed to represent the components and/or subsystems which contribute to the degraded state capability levels in each capability category (or element of the VL3 vector). These fault trees consist of a list of critical vehicle components that, if killed, result in that particular capability level being satisfied. For a particular capability category, a capability level is achieved when no uninterrupted path can be traced from top to bottom in the fault tree. The fault tree path configurations can be described as having components arranged in series or in parallel or as some combination of the two. If listed in series, the loss of any component causes an interruption in the path whereas those components listed in parallel must all be killed to interrupt the path. The components listed in the fault trees can represent either a single critical component or a system of critical components. The systems of components are usually developed into fault tree configurations during the criticality analysis.

There may also be a certain variability inherent in the processes of penetration, fracture mechanics, fluid leaks, and so on. If it exists, such variability would be a characteristic of the mapping function; that is, two applications of a mapping function to the same point in its domain could result in two different image points in its range.

b. Repeated Mappings and Probability Distributions. Consider the following procedure: Construct spaces at Levels 1 and 2 (VL1 and VL2) as described above. Also construct a "scorecard" at Level 2 which allows one to count how many times each damage state point in VL2 is reached. Then select only one set of initial conditions (a fixed point in VL1) and iterate the mapping O12, counting the number of times each point in VL2 is reached. It is clear that, following a large number of mappings, the information in the scorecard provides an indication of the likelihood that a certain damage state point in VL2 will occur from a given set of threat-target initial conditions in VL1. In fact, it is a straightforward process to infer from the scorecard information a probability distribution associated with the mapping and the initial conditions. The boxes marked "EVENT COUNTER" or "STATE COUNTER" in Figure 2 represent such scorecards.

In principle, the process could be repeated for several sets of initial conditions. In this way, one can arrive at an understanding of the stochastic nature of the physics or engineering underlying the O12 and O23 mappings.

Once the spaces are defined at each level and the mappings (O12, O23) are known for a particular vulnerability problem, then the analysis process can proceed. Selecting a set of initial conditions for threat-target interaction, one applies the O12 mapping to determine a damage state vector in VL2. Using that damage state vector as the domain point, one then applies the O23 mapping to determine a loss-of-capability vector in VL3. By repeated application of the O12 mapping from the same initial conditions, one can infer the likelihood of occurrence of each of the damage state vectors. Similarly, by repeated application of the O23 mapping to the same damage state vector, one can infer the likelihood of occurrence of each loss of capability.

The probability distribution of loss-of-capability vectors (degraded states) provides a much fuller description of the damage to the vehicle than does the traditional DAL metric. The distribution describes, in detail, the frequency and degree of the damage to each of the capability categories. The higher resolution of the DSVM provides information which is aggregated early (and thus lost) in the DAL process. For example, using the Degraded States distribution, the frequency of inflicting one, two, three, or four crew casualties can be determined. Also, the probability of a particular capability level in one capability category occurring simultaneously with a particular capability level in another capability category can be calculated. For example, it may be of interest to know how probable it was to have no firepower damage, yet still have crew and/or communications damage.

It is essential to appreciate two points:

1. These likelihoods, or probabilities, are functions of the mappings, and not of the spaces; if the mappings are changed, the probabilities which they associate with the vectors in the spaces will change.

2. The mappings have their domains and ranges in the V/L spaces, not in the sets of probabilities.

c. **Non-invertibility.** It is also important to realize that the mappings O12 and O23 are not, in general, invertible. That is, given a capability state vector in VL3, it is not possible to determine which damage state vector in VL2 was mapped into it by O23. In fact, there will generally be numerous damage state vectors which could produce, under O23, a given capability state vector.

A capability state vector in VL3 could be (M=0,F=1,C=1), indicating full firepower and crew capability, but no mobility. Notice that this piece of information by itself reveals nothing about why there is no mobility. Since the information does not survive in the capability state vector, the mapping O23 is clearly not invertible. Stated another way, the O23 mapping is "many-to-one" (or "many-to-many"). Similarly, O12 is not invertible; it, too, is many-to-one or many-to-many.

The consequences of this non-invertibility can be significant, particularly impacting the development process for military equipment.

4. Impact of Cardinality

It has been implied by the previous paragraphs that a combination of testing and modeling can be used to characterize system performance. As was noted in the previous section, the cardinalities of VL1, VL2, and VL3 could be finite or infinite. If the cardinality of VL2 is finite, it may be possible (though very expensive) to examine, through testing and simulation, the full spectrum of images of VL2 in VL3 under the O23 mapping. If the cardinality of VL2 is infinite, this is simply not possible.

Similarly, if the cardinality of VL1 is infinite (which is quite certainly the case in the real world of continuously-varying coordinate systems, masses and velocities), then it is clearly impossible to analyze every aspect of O12. Thus, the best which can be hoped for is to identify a reasonable approximation to O12, and to O23 as well. This is where the introduction of stochastic simulation into the process can pay off handsomely.

V. Relevance of the Taxonomy to the Vulnerability Analysis Process

1. Initial "Set-up" of Problem

Given a completely defined threat and target, how does one construct the appropriate V/L spaces for a given problem and determine and/or approximate the mappings between them? The first step in any analysis process is to determine the required precision. This requirement will dictate the level of detail required in computer target descriptions, the level of precision needed in test instrumentation and data reduction, the number of components identified as critical, and the level of performance capability testing to be done. (It seems reasonable that precision in the results of an analysis depends upon the level of detail in the target description. However, the quantification of this dependence is most difficult in practice.)

Having determined the required precision, the analyst quantifies and enumerates all relevant sets of initial configurations. Similarly, having identified the critical components and having decided to specify the damage states in terms of those components, it is possible to construct a VL2.

The elements of the VL3 vectors must reflect the capabilities to be evaluated for the target. Suppose these vectors have three elements corresponding to Mobility, Firepower, and Communication. The "granularity" of these elements is arbitrary, as was that of the elements in VL1 and VL2. For example, it would have been possible to have subdivided "Mobility" into "Ability to Go" and "Ability to Stop". This decision is again a reflection of the required precision which was discussed above. If it is somehow determined that greater precision is required, the dimensions of each element will need to be increased appropriately.

At this stage, the spaces are populated with vectors and their dimension has been set based upon some anticipated level of detail necessary to satisfy the requirements of the analysis. These spaces and the vectors in them represent the total universe of states for the problem; no initial conditions, damage states, or capabilities outside these spaces will enter into the analysis.

It might also be necessary to specify the allowed values that each element might assume. The coarsest graduation is binary; a capability is judged as either present (1) or absent (0). At the other extreme, each capability-designating-element could be a continuous variable. Intermediate are discrete formulations in which each element may have one of only a few allowed values.

It remains to characterize the mappings. For the O12 mapping, one may need algorithms for such damage mechanisms as penetration, shock, overpressure, fire and toxic fumes, depending upon the threat. All pertinent damage mechanisms must be identified and modeled, using a mix of empiricism and theory as appropriate. Essentially, the O12 mapping is characterized by the physics of the threat-target system.

In order to characterize O23, engineering measurements and/or modeling must be used. For example, there may be many ways of impeding the target's mobility. The impact of specific target damage is not easily assessed theoretically, and may thus require extensive testing for full and adequate characterization of the mapping in order to quantify the capability loss relative to the system's baseline performance.

It is worth reiterating that the spaces can all be formulated without anything more than a complete knowledge of system design and threat attack parameters. Defining the mappings requires testing and physics or engineering judgment. This points out yet another benefit of this V/L taxonomy: The sharp delineation made between the conditions (state-vectors) and the damage/degradation phenomenology (mappings) helps to focus attention upon the areas in which the essential shortcomings lie.

2. Extraction of Results for End-Uses

To this point, the discussion has been limited to the vulnerability analysis process, the results of which are specific, quantifiable, observable measures. However, for various analytical purposes, one must also be equipped to make more general assertions concerning the military utility of actual or hypothesized weapon systems. For example, to use vulnerability data in all its fine detail may be prohibitive. The remedy is to coalesce several data into a few numbers, weighting each datum based upon tactical/mission related probabilities.

Figure 3 provides a notional scheme which shows how such a statistical aggregation is formed. The battlefield utility of the target is broken into its potential mission components. Each component is further broken down until, ultimately, each branch ends on a specific target capability degradation (VL3 point). Since each branch has been weighted, it is then a straightforward task to "roll-up" an overall weighted loss of battlefield utility.

As an example of the processes outlined in this report, consider the following vulnerability analysis problem: Suppose a truck encounters a blast mine. The points in VL1 might look like

{[TRUCK],[MINE: blast parameters],[COORDINATES],[EVENT TIME]}

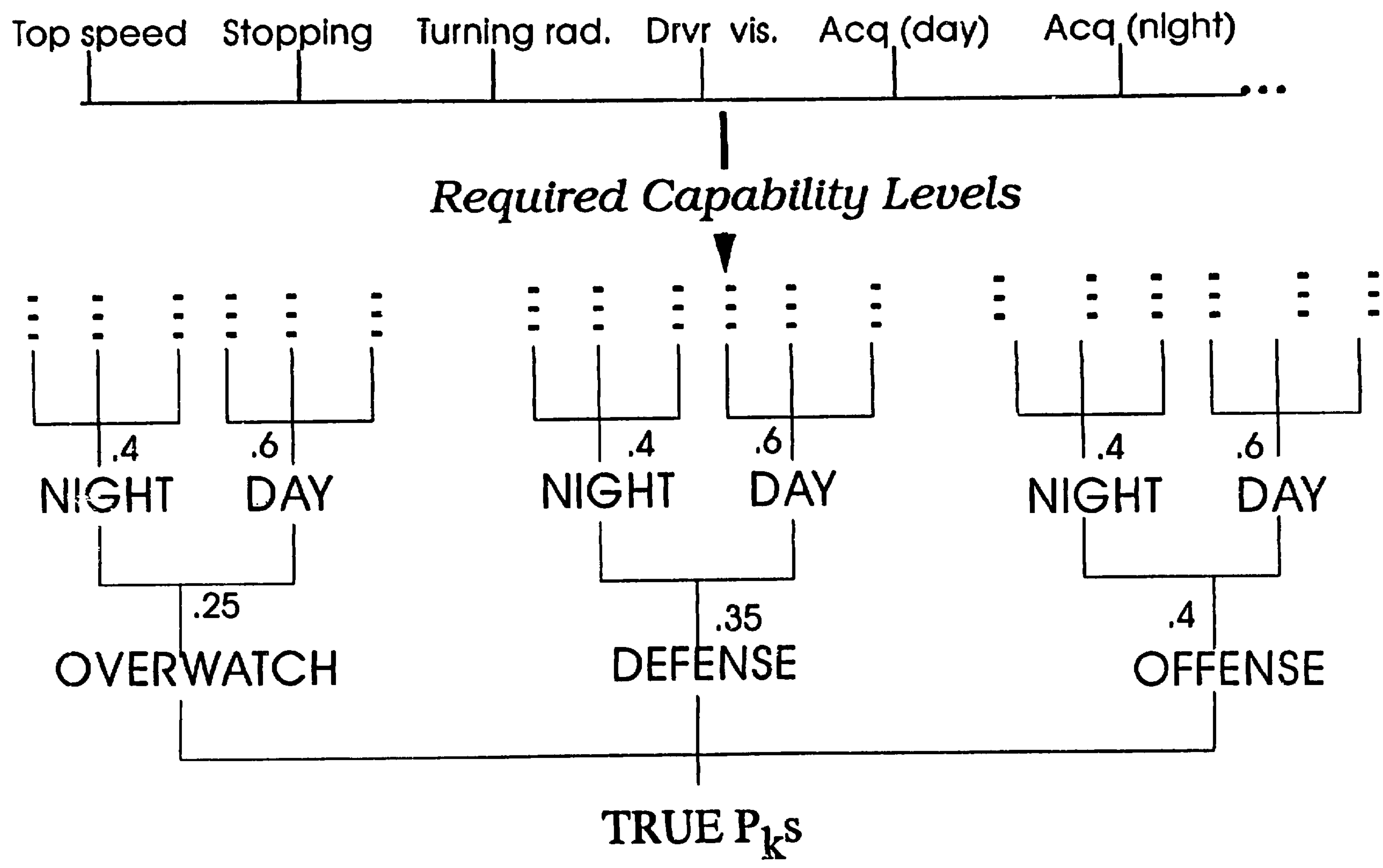

Figure 3. Aggregation to Level 4

Several replications would be needed to sample adequately the variability inherent in the encounter. However, for this example, we consider only two replications, resulting in two damage vectors in VL2

Truck 1: {...,0.2,...,<0.1,...,time of assessment}
Truck 2: {...,0.0,...,0.8,...,time of assessment}

where the generic form of the damage vector is

{...,[steering linkage damage],...,[radiator damage],
...,time of assessment}

Note that, in the first replication, the truck received slight damage to both the steering linkage and the radiator. In the second, no damage was done to the linkage, but significant radiator damage occurred. In an actual analysis, such differences between replications could result from any of a number of stochastic factors, such as variability in exact point of mine functioning relative to the truck, variability in hardness in truck components, etc.

Continuing with this example, it is now necessary to relate the (two) damage states to the resulting degradation in capability of the truck. A typical Degraded States vector in VL3 for this problem might be:

{[MOBILITY],[CREW],[COMMUNICATIONS],[time of capability assessment]}.

Based on the damage vectors produced above, only mobility is affected. It is also clear that a finer level of granularity is necessary if any distinction is to be made between the results of the two shots. The VL3 vectors could be refined to a form such as

{...,[TOP SPEED],...,[STEERING],...,[TIME TO ENGINE FAILURE],
...,time of capability assessment}.

Now, note that not all copies of the same truck will respond identically to the same damage. For example, the work of White et al.[13] has shown significant variation in failure times for identical engines with identical damage. Thus, the variation in system response to each damage state should be adequately sampled.

For this example, we replicate each O23 mapping twice, resulting in four possible degraded capability states (VL3 points) from the two damage states (VL2 points).

Truck 1, Test 1: {...,0.9,...,0.8,...,3 hrs,...,time of cap. assess.}
Test 2: {...,0.6,...,0.8,...,2.5 hrs,...,time of cap. assess.}
Truck 2, Test 1: {...,1.0,...,1.0,...,5 min,...,time of cap. assess.}
Test 2: {...,1.0,...,1.0,...,18 min,...,time of cap. assess.}

Now, assume there are two missions against which the truck's capabilities are to be assessed.

Mission 1: Hard surface road, drive 20 miles in 30 minutes or less.
Mission 2: Cross-country, drive 10 miles in 2 hours or less.

Evaluated against these missions, and based on a go/no go (0 or 1) system, the "kill" analysis would look like

	Truck 1		Truck 2		Pk
	shot 1	shot 2	shot 1	shot 2	
Mission 1	0	1	1	1	0.75
Mission 2	0	0	1	1	0.50

Note that this process produces a frequency distribution. Multiple replications would produce multiple damage vectors which would map onto multiple capability states. These can then be "rolled up", as demonstrated for the four states in the example. The number (0.75 or 0.5 above) represents the fraction of all samples in which the mission requirements are not met; i.e., the frequency (from which a probability can be inferred) with which the selected set of initial conditions result in a mission kill.

It must also be noted that the assessment of the second mission did not require another vulnerability analysis to be done. Rather, once the degraded capability vectors were found, the mission assessment was accomplished by a simple "roll-up". Thus, having brought one analysis to Level 3, the analyst is prepared for any mission from any customer.

By comparison, the Pk from the DAL for the truck is 0.5 for any and all missions. Clearly, the new methodology is significantly more flexible - and accurate.

VI. Inclusion of Degraded States Metrics in the JANUS Force-Level Model

This section describes current, on-going work with the Training and Doctrine Command Analysis Center-White Sands Missile Range (TRAC-WSMR) to include degraded states-type metrics in the JANUS force-level model. Briefly, JANUS is a highly detailed, two-sided interactive stochastic combat simulation that is capable of playing armored vehicles, infantry fighting vehicles, artillery, fixed wing and rotary wing aircraft. The model simulates two opposing forces which are simultaneously directed and controlled by two sets of players, one set for each force. The purpose of this study is to prove the feasibility of using Degraded States vulnerability data in a highly detailed force level combat simulation. The combat scenario that was selected for this study contained approximately 250 direct fire engagements. Only direct fire weapons were used in this scenario because degraded states data were readily available and there was a desire to limit the scope of this initial trial.

When a direct fire engagement takes place in JANUS, a "probability of kill", based on the DAL methodology, is selected from a look up table according to the engagement parameters (range, azimuth, munition, target, etc...). This number is a view average loss of function value but is used as a probability of no capability. A random number is then drawn to determine if the vehicle is killed or not killed. There are many well known shortcomings to this approach, all of which degraded states eliminates (see references 4 and 5).

BVLD's proposed solution for this initial trial is to write a "black box" that could be compiled and linked into JANUS that would take care of determining a vehicle's degraded state. This black box would consist of a subroutine and all of the supporting cell-by-cell data and would be called whenever a direct fire engagement takes place. This subroutine will do several calculations (range, impact azimuth, impact location to name a few) and then would look up the appropriate degraded states data from the appropriate cell. View average numbers will not be used with the degraded states approach. It was decided to calculate the impact location of the munition and use the vulnerability calculations from that exact location on the target.

It is ultimately hoped to be able to provide, for JANUS, a package which would do the vulnerability calculations in real time instead of looking up pre-calculated vulnerability data. This would be done during the course of the game as each engagement takes place and for the specific engagement parameters (i.e. calculate the degraded state for 23 degrees azimuth instead of looking up the pre-calculated degraded state for 3C degrees).

Currently, personnel at TRAC-WSMR are examining ways to use the degraded states data. There are many implementation details that will be worked out between TRAC-WSMR and BVLD; for example, is a vehicles probability of hitting a target reduced if it has a reduced delivery accuracy capability or how much is the mean time to acquire increased when a vehicle has a reduced target acquisition capability?

VII. Extensions of the V/L Process Structure

The concept of the Process Structure has application outside the realm of vulnerability/lethality analyses. The premise for this statement can be found in the earlier discussions in this report. All events, through the determination of remaining capabilities, are engineering observables or measurables; that is, one could physically observe or measure these phenomena in the field. Consequently, there are a number of additional uses for the process structure that would permit analyses across the spectrum of Army concerns for a combat system based on the same set. This would increase clarity about which capabilities are important and provide a tool for communication among the analysis community. Several such applications are apparent. These are the 1) Reliability, Availability, and Maintainability (RAM) analyses; 2) Battle Damage Repair (BDR); 3) Nuclear, Biological and Chemical (NBC) Contamination Survivability; 4) Operational Requirements Documents (ORDs); 5) comparison of analytical with experimental; and 6) force-level wargames (as shown in the previous section). The ability to clarify the operational requirements of a system by identifying its required functions provides a sound basis for communications between the user, the developer and the analysis community throughout the acquisition life cycle of the system. Applying the same analytical approach to such diverse areas as V/L, RAM and BDR allows one to evaluate the major aspects of the acquisition cycle using the same process. A more detailed discussion of these extensions of the V/L Process Structure can be found in reference 14.

VIII. Conclusions and Recommendations

A taxonomy has been developed for the vulnerability analysis process. It has been shown that this taxonomy represents an appropriate and internally consistent mathematical foundation for vulnerability science, providing a framework for analytical processes and a means for identifying knowledge gaps. The DSVM is a prototypical example of the O23 mapping process, and its application demonstrates the value of the process structure developed in this report. As the example clearly shows, the DSVM provides a much more detailed assessment of a vehicle's performance capability than is possible with the traditional DAL approach.

One of the most important advantages of the taxonomy developed in this report is the fact that it provides a mathematical framework within which new analytical procedures may be developed in a systematic fashion. For example, the astute reader will have surmised that there is likely an algebra of the vectors in the spaces which can be defined, with a "norm" or distance, and a binary operator for combining two vectors. This algebra is being pursued and is the subject of a report now in progress. The advantage to such work is the ability to answer for the first time, in a precise mathematical sense, the question of what is meant by two shots on a target being "close." Moreover, finding a set of basis vectors for, say, VL2, would essentially identify the most important "shots" to test against a system to learn its vulnerabilities. If the O12 and O23 mappings can be made continuous, then there is a great deal of mathematical formalism concerning approximation of continuous functions which can be brought to bear on the problem of modeling the physics and engineering of the vulnerability analysis process.

The growth potential has already been demonstrated in a dramatic fashion by the fact that the DSVM is currently being applied to investigate problems in RAM and BDR. It should also be noted that the process structure is applicable to all vulnerability problems across the services; it is not limited to ground combat systems. This is evidenced by the fact that the taxonomy discussed in this report has been used as the basis for the Target Interaction Lethality/Vulnerability (TILV) Master Plan, being developed for the Joint Directors of Laboratories under the auspices of the Office of the Secretary of Defense.

At this time, it is impossible to predict the degree to which such mathematical formalism, with rigorously defined entities, will be able to resolve the problems noted with past vulnerability analysis methods. However, if nothing else results from this exercise, the taxonomy and associated vocabulary developed have already proven to be extremely useful to those who now routinely use it. The Levels of results, the meaning of a Space of state vectors, the constituents of a mapping -- these concepts have considerably sharpened information and idea exchange in a wide range of vulnerability applications, including managerial and operational issues, as well as methodological developments.

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